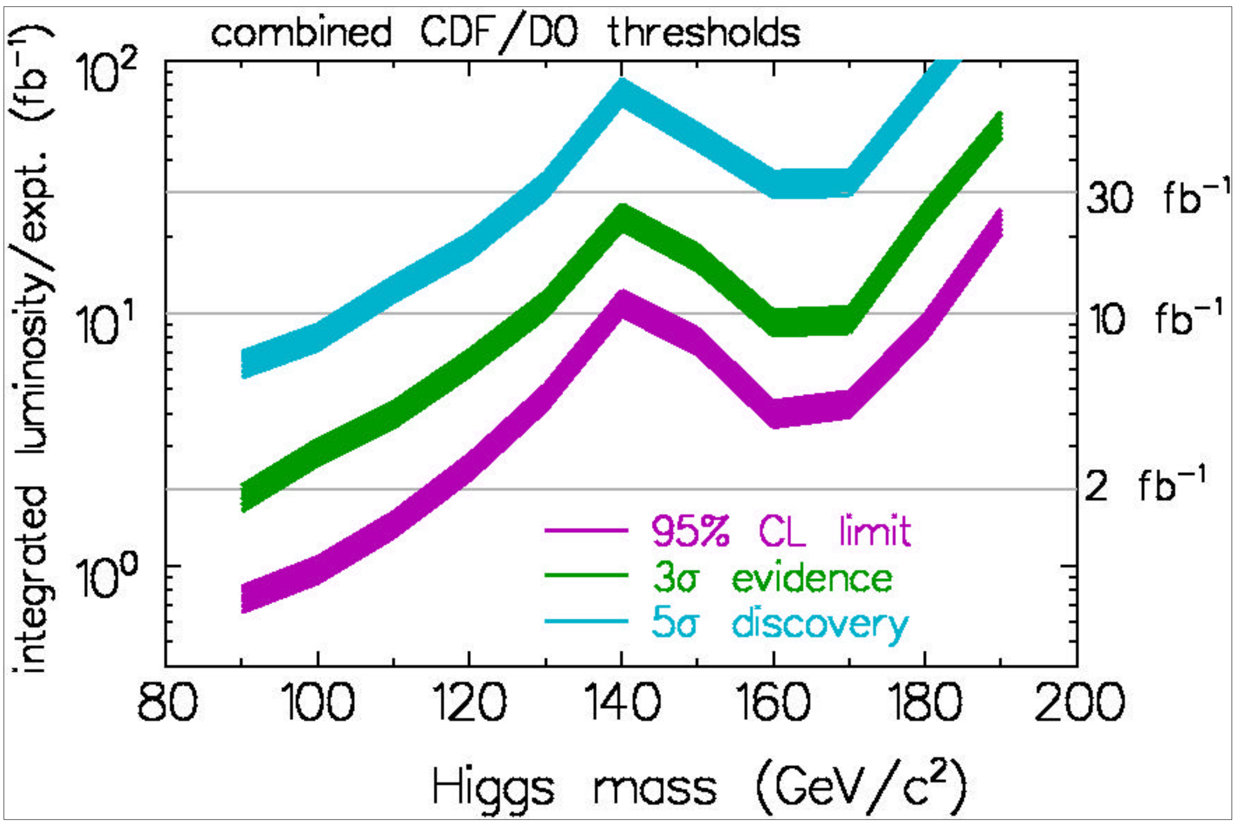
DØ Run IIb Upgrade Technical Design Report



PHYSICS GOALS

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1 INTRODUCTION

Proton-antiproton collisions at $\sqrt{s} = 2$ TeV have proved to be a very fruitful tool for deepening our understanding of the standard model and for searching for physics beyond this framework. DØ has published more than a hundred papers from Run I, including the discovery and precision measurements of the top quark, precise tests of electroweak predictions, QCD tests with jets and photons, and searches for supersymmetry and other postulated new particles. With the addition of a magnetic field, silicon and fiber trackers, and substantial upgrades to other parts of the detector, DØ has started with the goal of building on this broad program, taking advantage of significantly higher luminosities, and adding new measurements in b-physics. The strengths of the DØ detector are its liquid argon calorimetry, which provides outstanding measurements of electrons, photons, jets and missing E_T; its large solid angle, multi-layer muon system and robust muon triggers; and its state of the art tracking system using a silicon detector surrounded by a fiber tracker providing track triggers.

A series of physics workshops organized by Fermilab's Theory group together with the CDF and DØ collaborations has mapped out the physics terrain of the Tevatron in some detail. It is clear from the very large amount of work carried out in these meetings and described in the reports[1] that integrated luminosities much higher than the $2 fb^{-1}$, which was the original goal of Run II, add significantly to the program. While all areas of physics benefit from increased statistics, it is the very real possibility of discovering the standard model Higgs boson (or its supersymmetric versions) and/or supersymmetric particles or other physics beyond the standard model, that forms the core motivation for the Laboratory's luminosity goal of 15 fb^{-1} per detector. We have therefore used the most promising Higgs discovery channels as benchmark processes for the Run IIb upgrade, which is described in this design report, and have optimized the detector configuration for them. All other high p_T physics programs benefit from this detector optimization (though for the QCD and b-physics programs the benefits will be balanced by decreased trigger allocations and some loss of geometric acceptance). In the following, we discuss physics requirements on the Run IIb upgrade imposed by Higgs searches and their implications for other high p_T physics programs.

[1] http://fnth37.fnal.gov/run2.html

2 STANDARD MODEL HIGGS BOSON SEARCHES

The highest cross section Higgs production channel at the Tevatron is the gluon fusion reaction $gg \rightarrow H$. Unfortunately, for Higgs masses below about 135 GeV, its dominant decay mode is to $b\bar{b}$ and is swamped by QCD production of b-jets. The most promising Higgs search strategy in this mass range is to focus on associated production of a Higgs with a W or Z boson, $p\bar{p} \rightarrow WH$ and $p\bar{p} \rightarrow ZH$. The leptonic decays of the W and Z enable a much better signal to background ratio to be achieved, but one must pay the cost of a production cross section about one fifth that of inclusive production together with the leptonic branching ratios of the vector bosons. This relatively low signal cross section times branching ratio motivates the need for high integrated luminosity. In turn, the need for high integrated luminosity forces the accelerator to operate in a mode where each high p_T event is likely to be accompanied by a significant number of low p_T "minimum bias" events occurring in the same $p\bar{p}$ bunch crossing. The mean number of interactions $<n>$ is around 5 for a luminosity of $2\times10^{32}cm^{-2}s^{-1}$ at 132ns bunch spacing. This high occupancy environment is one of the main challenges for Run IIb.

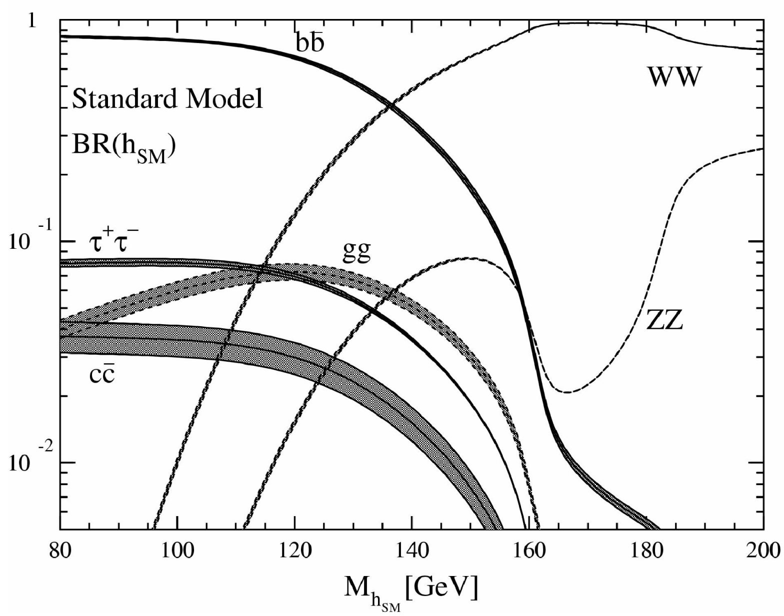

Figure 1 - Standard Model Higgs decay branching ratios as a function of Higgs mass.

Figure 1 shows the decay modes of the Standard Model Higgs in the mass range relevant to DØ. For Higgs masses below roughly 135 GeV, the Higgs decays dominantly to b-quark pairs, and for masses above this (but less than the $t\bar{t}$ threshold) the decay is dominantly to W and Z boson pairs. Thus, searches for Higgs boson in the low mass region $M_H < 135$ GeV must assume $H \rightarrow b\bar{b}$ decays. Searches for the lightest Higgs in supersymmetric models must also assume decay to b-quark pairs.

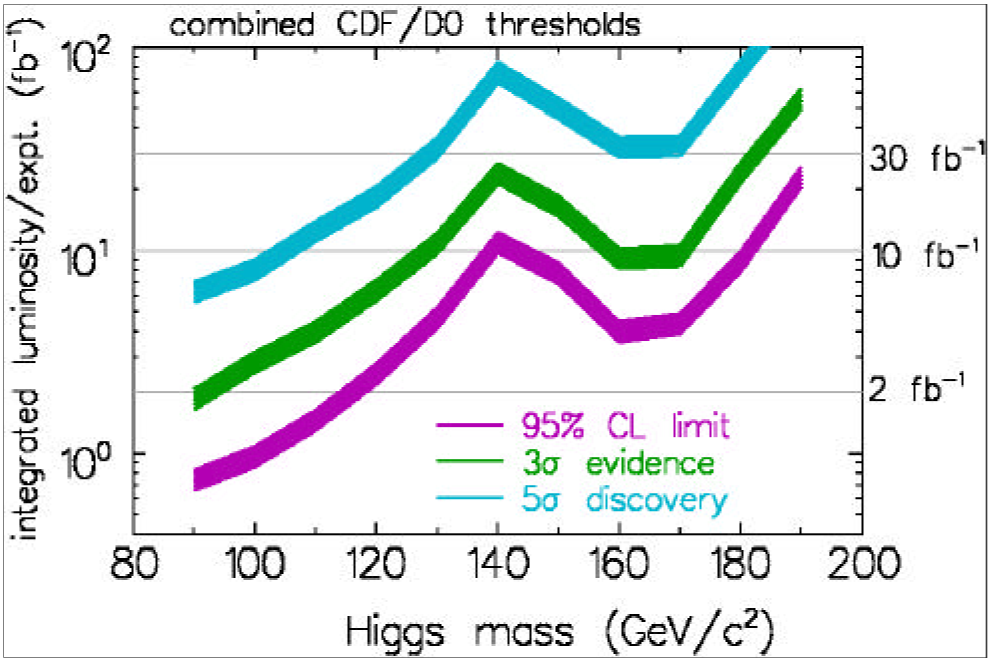

Figure 2 - Required luminosity as a function of Higgs mass for 95% C.L. exclusion, 3s evidence, and 5s discovery.

Figure 2 shows the luminosity required to exclude or discover a Standard Model Higgs at the Tevatron. This result assumes the expected Run IIa performance of both the CDF and DØ detectors. For 15 fb^{-1}, a 5σ discovery can be made for a Higgs mass of 115 GeV, a >3σ signal is expected for most of the mass range up to 175 GeV, and Higgs masses up to 180 GeV can be excluded if there is no sign of the Higgs.

As stated above, for Higgs bosons in the low mass range, the associated-production modes will be used for searches. The final states of interest are those where the W(Z) boson decays to charged leptons or neutrinos, and at least two b-flavored hadronic jets from the Higgs decay are selected. The dominant background arises from W(Z) bosons produced in association with jets from initial state radiation of gluons. Even in the associated production channels, the intrinsic signal to background for vector boson plus two jets is prohibitively small. However, the majority of the W(Z)+jets background contains light quark or gluon jets, while the Higgs signal is almost exclusively $b\bar{b}$. The ability to identify the b-jets from Higgs decay is the crucial first step in reducing the boson+jets background to a manageable level. The combination of b-jet identification, reconstructed dijet mass, and additional kinematic variables is used to improve the signal to noise to achieve the sensitivity shown in Figure 2. This result depends on the ability to identify b-jets with at least 50% efficiency and background contamination from light quark jets at the 1% level. Effective tagging of b-jets is one the most important physics objectives for the tracker system. It is likely that two tagged jets will be required to reduce the background to acceptable levels, so maximizing the tagging efficiency is most important.

The identification of b-jets can be done by exploiting either the relatively long lifetime of the b-flavored particles or by detecting leptons from semi-leptonic decay of b-quarks (or both). The first technique allows all decays to be considered, whereas the second method suffers reduced statistical precision because of the ~30-40% decay branching ratio of b-quarks to final states including leptons. The long lifetime of the b-quarks is reflected in a B-meson decay that occurs some distance from the primary beam interaction point. For b-flavored particles with energies expected from Higgs decay, the mean decay length is 2 mm, and the mean impact parameter is roughly 250 μm. Thus, efficiently and cleanly identifying these decays requires a detector with the ability to reconstruct tracks with an impact parameter resolution in the tens of microns. The most feasible technology for this is silicon microstrip detectors.

One of the low-mass Higgs signatures is particularly noteworthy: Higgs production in association with a Z boson, which decays into a neutrino-antineutrino pair, resulting in missing energy and two b-jets in the final state. One of the main strengths of the DØ detector is its good missing energy identification; yet to keep trigger rates under control the present threshold on the missing E_T trigger is about 35 GeV. A search for the Higgs boson in the ZH channel can certainly benefit from a lower trigger threshold. This can be achieved by implementing an efficient 2-jet trigger at the first trigger level and using information about displaced tracks at the second trigger level. The proposed calorimeter trigger upgrade will enable us to efficiently trigger on jets of moderate transverse energy, while the silicon track trigger upgrade will retain our ability to trigger on displaced tracks with the upgraded silicon tracker.

Searches for the Higgs boson in the intermediate mass region $135<M_H<200$ GeV/c^2 assume inclusively-produced Higgs decaying to WW* and ZZ*, where at least one of the vector bosons decays to leptons. Effective lepton triggering and identification, essential for vector boson detection, is important for Higgs searches in both low and intermediate mass regions. The tracking system plays a crucial role in electron, muon and, arguably, tau lepton triggering and identification. Leptons from W and Z decays are fairly energetic, with $p_T>20$ GeV/c. The requirement that we efficiently trigger on high-p_T tracks is the primary motivation for the track trigger upgrade and the cal-track match system, while the requirement that we efficiently reconstruct these tracks is an important design requirement for the silicon tracker upgrade.

Higgs production in association with $t\bar{t}$ has received a lot of attention recently[2]. Though low in cross section, this channel provides a very rich signature with leptons, missing energy, and 4 b-jets in the final state. B-jets produced in this process have higher energy than those in processes such as WH production. Tracks in such jets tend to be more collimated, emphasizing the need for robust pattern recognition in the high occupancy environment. Another challenge for this channel is ambiguity in b-jet assignment, which can be reduced if the charge of the b-quark can be tagged. Several methods for b-charge tagging have been developed so far, e.g. same side tagging, jet charge tagging. Having information about charge of tracks in the secondary and tertiary b-decay vertices could be invaluable to improve purity of these tagging methods. This puts additional emphasis on precise impact parameter reconstruction.

[2] J. Goldstein *et al.*, “ $p\bar{p} \to t\bar{t}H$: A discovery mode for Higgs boson at the Tevatron”, Phys. Rev. Lett. **86**, 1694 (2001).

It is important to note that Higgs searches at the Tevatron and at the LHC are complementary to each other. While LHC experiments[3] emphasize the $gg \to H \to gg$ channel, where Higgs is produced and decays via loop diagrams, the Tevatron's emphasis is on tree-level production and tree-level decay. For a Standard Model Higgs, the branching ratio to gg is very low, making it impossible to observe this channel at the Tevatron. However, some models predict a "bosophilic" Higgs, for which this decay mode is enhanced. Thus, high-energy photon identification is important for Higgs search beyond the Standard Model. Photon/electron separation is essential for high-purity photon identification. For this purpose the tracking system must ensure low fake track rate and a good momentum resolution.

3 PHYSICS BEYOND THE STANDARD MODEL

Searches for SUSY and strong dynamics will benefit from the requirements imposed on the tracking system by the Standard Model Higgs searches. SUSY extensions of the Standard Model predict two Higgs doublets with five physical Higgs bosons – two neutral scalars (h,H), one neutral pseudoscalar (A) and two charged bosons ($H^{\pm}$). Over much of the remaining allowed parameter space, the lightest neutral boson h behaves similarly to the Standard Model Higgs, and has a mass in the range 115-130 GeV, while the H, A and $H^{\pm}$ masses are larger. The standard model Higgs searches described above are, at the same time, searches for the lightest SUSY Higgs h. In addition, some Higgs cross sections are enhanced in SUSY, e.g. $p\bar{p} \to b\bar{b}(A/h)$ with A,h $\to b\bar{b}$ in a high $\tan b$ scenario. Efficient b-jet triggering, tagging, and b-charge identification is essential for Higgs discovery in these channels, which contain four b-jets. The charged Higgs boson can be detected in top decays or through pair production of H^+H^-, and decays to $b\bar{c}$ or $t^- n$, depending on $\tan b$. Again, good heavy flavor triggering, tagging, and tracking (for tau-lepton identification) are important. Studies have shown that the Tevatron can exclude almost the whole plane of SUSY Higgs parameters (m_A, tan β) at the 95% level, if no signal is seen in 5 fb^{-1}, and can discover at least one SUSY Higgs at the 5 standard deviation level with 15-20 fb^{-1} per experiment.

[3] M. Carena, S. Mrenna, C. Wagner, "Complementarity of the CERN LEP collider, the Fermilab Tevatron, and the CERN LHC in the search for a light MSSM Higgs boson" Phys Rev. **D62**, 055008 (2000).

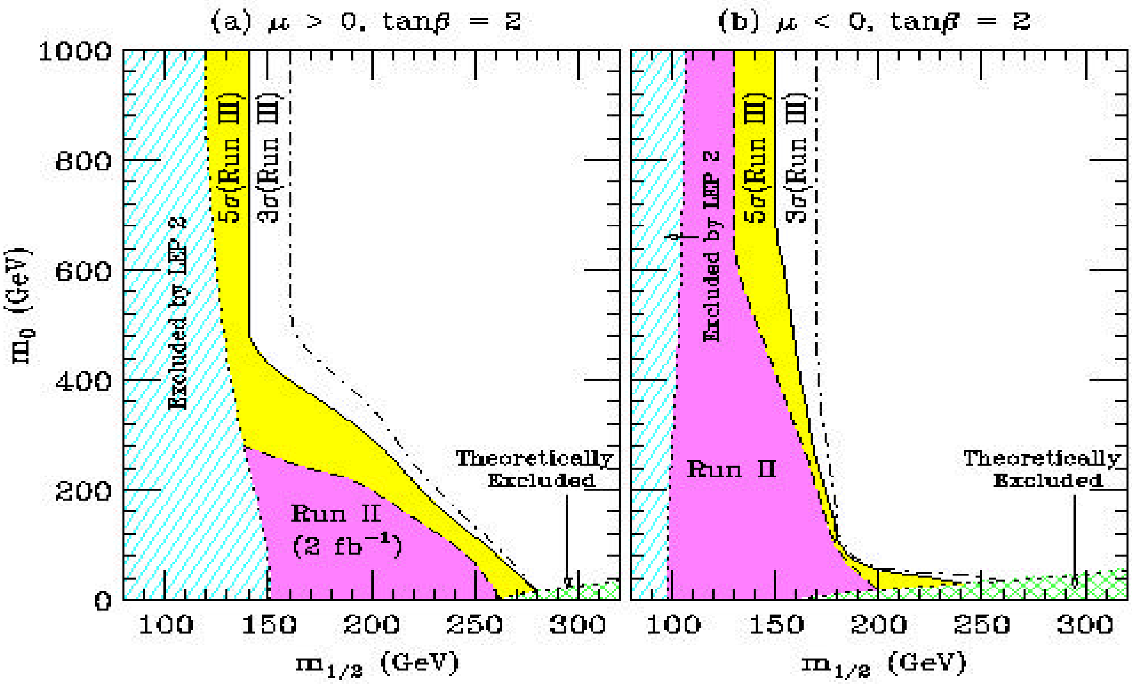

Figure 3 - Contours of 90% C.L. observation at Run IIa, 5σ *discovery, and 3s observation at Run IIb for* $p\bar{p} \to \text{SUSY particles} \to 3l + X$ *in the* $(m_{1/2}, m_0)$ *plane for tan*β*=2, (a)* μ*>0 and (b)* μ*<0.*

Direct searches for squark and gluino production, in jets and missing E_T final states (with or without one or more leptons), have been carried out at the Tevatron since its inception. These still have an important role to play, but once a few inverse femtobarns have been collected, the limits will have reached 400-500 GeV on squark and gluino masses and further improvements will be limited because of the production kinematics. The greatest gains in going from 2 fb^{-1} to 15 fb^{-1} will likely come in searches for lower cross section processes. One of the most promising ways to look for MSSM supersymmetry at the Tevatron is associated chargino-neutralino production: $p\bar{p} \to \tilde{c}_2^0 \tilde{c}_1^+; \tilde{c}_2^0 \to l\bar{l}\tilde{c}_1^0; \tilde{c}_1^+ \to l^+ n \tilde{c}_1^0$. This results in a very distinct signature of three leptons and missing energy[4]. Because of its low cross section this search will especially benefit from the increased statistics in Run IIb. The Tevatron's reach in this signature is presented in Figure 3. Note, that Run IIb will not only extend the area of search, but will reach the high m_0 region, which was not accessible before. Good lepton identification and the ability to trigger on low p_T leptons is of great importance for this channel.

The supersymmetric partners of top and bottom quarks – *stop and sbottom* - are often predicted to be lighter then other supersymmetric particles[5]. These particles will be produced strongly in $p\bar{p}$ collisions and thus are likely targets for supersymmetric searches. Decay products include

[4] S. Abel *et al.*, "Report of the SUGRA working group for Run II of the Tevatron", hep-ph/0003154.
[5] R. Demina, J. Lykken, K. Matchev, A. Nomerotski, " Stop and Sbottom searches in Run II of the Fermilab Tevatron", Phys. Rev. **D62**, 035011 (2000).

b-jets, and searches will require b-tagging. The pseudorapidity distribution of charged tracks produced in decays of these supersymmetric particles is very similar to that of Higgs decay products, as shown in Figure 4 for two distinctly different kinematic cases with very low energy jets in the final state (b) and with very high energy jets (c). In both cases the b-jets fall within the acceptance of the silicon tracker.

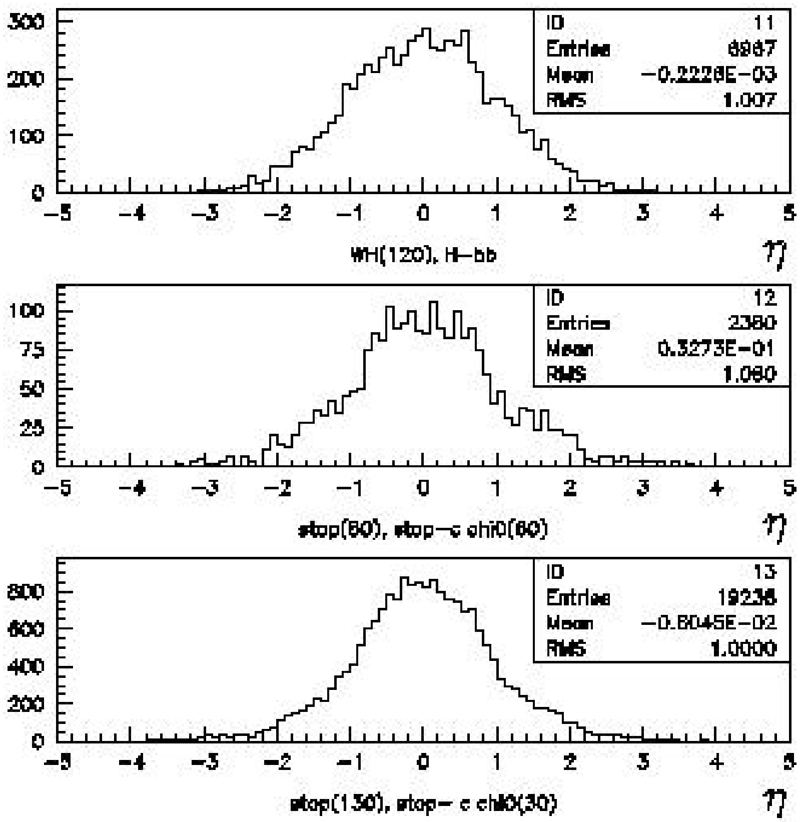

Figure 4 - Pseudorapidity distribution of charged tracks in
a) WH events (M(H)=120GeV/c²);
(b) light supersymmetric top decaying to charm and heavy neutralino
$(M(\tilde{t}) = 80GeV/c^2; M(\tilde{\chi}_1^0) = 60GeV/c^2)$ *;*
c) heavy supersymmetric top decaying to charm and light neutralino
$(M(\tilde{t}) = 130GeV/c^2; M(\tilde{\chi}_1^0) = 30GeV/c^2)$.

Gauge-mediated supersymmetric models predict signatures rich in photons[6]. Interest in these models was sparked by the CDF observation of an $e^+e^-\gamma\gamma \not\!\!E_T$ event[7]. Though no other events

[6] R. Culbertson *et al.*, "Low scale and gauge mediated supersymmetry breaking at the Fermilab Tevatron Run II", hep-ph/0008070.

[7] CDF collaboration (F. Abe *et al.*), "Searches for new physics in diphoton events in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, Phys Rev. **D59**, 092002 (1999).

have been found, photonic signatures are worth investigating in Run IIb. The phenomenology of extra dimensions also predicts signatures rich in photons[8].

Alternatives to SUSY are strong dynamics models, for example technicolor or topcolor. Technicolor models predict the existence of technibosons decaying to heavy flavor and gauge bosons[9], e.g. $p\bar{p} \rightarrow W\rho_T, \rho_T \rightarrow b\bar{b}$. Such searches give vector boson plus heavy-flavor-jets signatures, just like the Higgs search, and will benefit from the detector optimizations motivated by Higgs signatures. More recent topcolor models[10] emphasize non-standard behavior of the top quark and thus could be detected indirectly with thorough studies of top quark properties, or directly through observation of anomalous tb production or production of non-standard Higgs-like bosons decaying to heavy flavor jets.

[8] T. Rizzo "Indirect collider tests for large extra dimensions", hep-ph/9910255.
[9] E. Eichten, K. Lane and J. Womersley, "Finding Low-Scale Technicolor at Hadron Colliders", Phys. Lett. **B 405,** 305 (1997).
[10] C. Hill, "Topcolor assisted Technicolor", Phys. Rev. **D49**, 4454 (1994).

4 STANDARD MODEL PHYSICS

The searches for new particles will be complemented by precision measurements of the quanta of the standard model, which provide indirect constraints on new physics, and which will provide the detailed understanding of backgrounds that discoveries will require.

The Tevatron is entering a new era for top quark physics. Greatly increased statistics will be combined, in DØ, with much improved signal sample purity made possible by silicon vertex b-tagging. We anticipate significant improvements in the precision of the top quark mass measurement, which should reach a level of ~2 GeV with 2 fb^{-1}. The additional statistics of Run IIb should allow a precision of ~1 GeV. Single top production (through the electroweak coupling of the top) has never been observed. Measurement of the cross section would allow the CKM matrix element $|V_{tb}|$ to be extracted. With 2 fb^{-1}, the cross section can likely be measured at the 20% level, allowing $|V_{tb}|$ to be extracted with a precision of 12%. With 15 fb^{-1}, this uncertainty could be roughly halved. The signatures for top pair and single top production involve vector bosons and heavy flavor jets, just like the SM Higgs. They must be understood in detail for the Higgs search and they will benefit from the detector upgrade.

Precision measurements of the properties of the weak boson will continue to be an important part of the Tevatron program. The W-mass precision should reach 30 MeV per experiment with 2fb^{-1} and 15-20 MeV may be achievable with 15 fb^{-1} (theoretical uncertainties are a big unknown in this extrapolation). A W-mass measurement δm_W = 20 MeV combined with a top mass measurement δm_t = 2 GeV will be sufficient to constrain the Higgs mass between roughly 0.7 and 1.5 times its central value[11]. For a 100 GeV best fit, the upper limit of 150 GeV would be well within the Tevatron's region of sensitivity. Such a comparison between direct and indirect Higgs mass measurements would be very interesting whether or not a Higgs signal is seen, as shown in Figure 5.

[11] M. Grünewald et al., hep-ph/0111217 (2001).

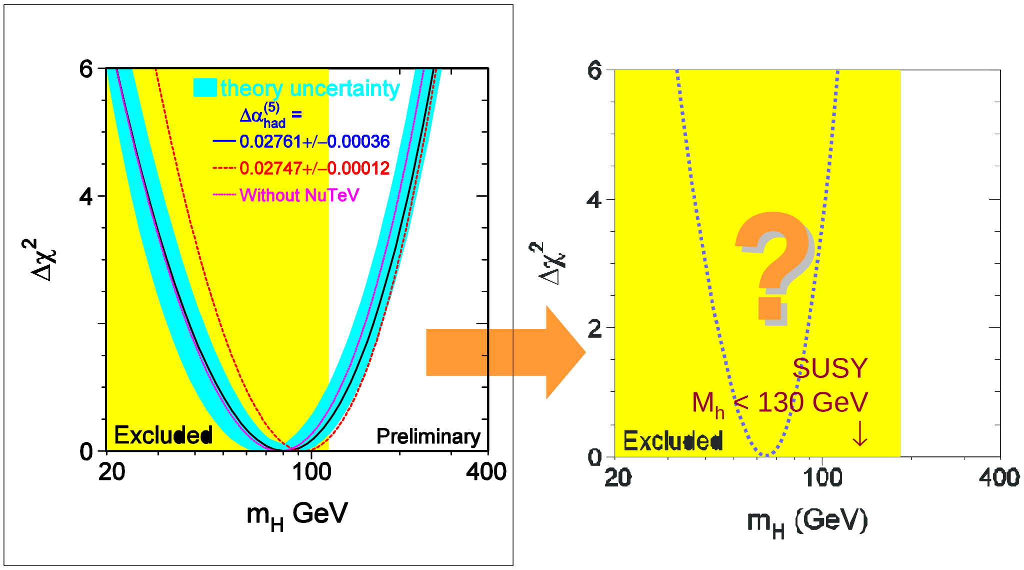

Figure 5 - Higgs exclusion regions from direct searches (yellow region) confronting indirect constraints from electroweak parameters, top and W mass measurements(blue parabola). The plot on the left is the present situation (summer 2002) and the plot on the right shows a putative future situation including Run IIb results.

Tests of QCD are important at the Tevatron, both as "engineering" measurements and as probes of strong interaction physics. In the former category, measurements of jet production have reached new levels of precision in Run I and are forcing a significant overhaul of the parton distribution functions used in hadron colliders, because the errors on these pdf's must henceforth be treated rigorously. Tevatron jet data from Run II will likely provide strong constraints on pdf's and will be an important input to the global fits. In the latter category, many QCD processes have relatively low cross sections and will benefit greatly from increased datasets available in Run II. Examples are jet production at high-x (jet E_T above about 400 GeV) where the behavior of the cross section is still somewhat uncertain; vector boson plus jet processes, which may be used to determine the strong coupling constant; and diphoton production, which is an important background to Higgs searches at the LHC. In Run I, DØ accumulated about 200 $\gamma\gamma$ candidates. This will increase to 4000 with 2 fb^{-1}, which is still not a huge number, and to 30,000 with 15 fb^{-1} of integrated luminosity.

While the DØ detector is not strongly optimized for b-physics, it possesses a number of features that allow it to make significant contributions in this area. As one example, the low-p_T muon triggering and $J/\psi \rightarrow ee$ triggers will allow a competitive measurement of sin 2β in $B \rightarrow J/\psi\ K_S$ events. With 2 fb^{-1}, sin 2β could be determined to $\pm$0.07; 15fb^{-1} would reduce this uncertainty by almost a factor of three. Of course, the b-physics program will have to operate within a trigger menu that is constrained by the need to cover the high p_T physics priorities of the experiment.

5 SUMMARY OF PHYSICS OBJECTIVES

The DØ Run IIb upgrade is optimized for Higgs boson observation in the $110<M_H<180 GeV/c^2$ mass region. A low-mass Higgs boson decays predominantly to $b\bar{b}$, and thus efficient b-tagging is of paramount importance to Higgs boson searches. Trigger upgrades that allow the efficient recording of Higgs events are also crucial elements of the upgrade. Lepton identification, crucial for much of the Run IIb physics program, requires efficient triggering and tracking of high p_T tracks in a high occupancy environment, in conjunction with the excellent muon and calorimeter of the DØ detector. $Ht\bar{t}$ production puts additional, more stringent, constraints on efficient tracking and secondary and tertiary vertex reconstruction.

It is clear that the entire DØ physics menu of searches, top quark physics, electroweak measurements, QCD, and even b-physics, will benefit from Run IIb. The upgraded tracker will ensure efficient tracking in a high occupancy environment, the upgraded trigger will allow the required data samples to be recorded with high efficiency, and efficient heavy flavor tagging will be a key ingredient for final states with b and c-quark jets.

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